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High-Speed Direct Modulation of Waveguide-Coupled Metal-Cavity Nano-Light-Emitting Diodes

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Future optical interconnects require ultra-small light sources working efficiently (~fJ/bit) at tens of Gb/s speeds [1]. This will be of paramount importance for the development of ultrafast computing and optical communication systems. Electrically driven nanolasers recently succeeded in achieving lasing in sub-µm sized metallo-dielectic cavities [2]. Nonetheless, high losses in metal cavities make it challenging to accomplish efficient lasing at room-temperature (RT), while their predicted high-speed modulation properties have remained unexplored.

As an alternative, nanoscale light-emitting diodes (nanoLEDs) using plasmon waveguides [3] and antenna enhanced waveguide-coupled nanoLEDs [4], appeared recently as promising light sources that are not limited by low-quality cavities, can operate without a threshold and emit in a single spatial mode. Despite these efforts, the proposed sources display negligible output power and ultra-low efficiencies (~10^{-7}), preventing the characterization of their modulation characteristics, and therefore limiting our understanding of their true potential for on-chip interconnects.

In this work, we investigate the high-speed dynamic properties of metal-cavity nanoLEDs, Fig. 1(a), operating at telecommunications wavelengths with nW optical output power, Fig. 1(b). Under direct electrical modulation we achieve sub-nanosecond electro-optical response revealing potential for multi-Gb/s modulation speeds.

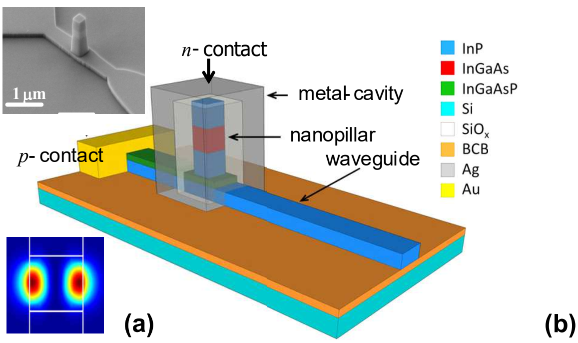

Fig. 14. (a) Schematic of the waveguide-coupled metal-cavity nanoLED. The inset shows a scanning electron microscope (SEM) picture with the fabricated nanopillar (top-left), and the simulated $|E|^2$ of the in-plane polarized mode supported by the cavity within the InGaAs active region (bottom-left). (b) Typical L-I characteristics measured at 9.5 K and at RT and model fit (dashed curves). The inset shows a typical spectrum emission at RT.

The nanoLED is a nanopillar metal-dielectric cavity coupled to a InP-waveguide on a III-V membrane bonded to silicon [5]. The nanopillar (~300nm side length) consists of a semiconductor epilayer structure with an intrinsic InGaAs active region, covered with a SiO_2 layer and then encapsulated with a silver cladding forming a metallo-dielectric cavity which redirects a sizeable fraction of spontaneously emitted photons into a single guided mode. Light-current (L-I) curves of a nanoLED are displayed in Fig. 1(b), showing typical optical emission ~1.53 μm with nW (tens of nW) output power at RT (low T) measured from a grating coupler at tens of μA bias levels. The corresponding efficiency for waveguide emission is estimated as 10^{-4} and 10^{-2} at RT and low T, respectively.

We employed time-correlated single-photon counting to experimentally investigate the high-speed direct modulation of fabricated metal-cavity nanoLEDs. The devices were modulated employing a pulse pattern generator (PPG) while setting a dc bias through a bias-T. The electroluminescence was coupled into a single mode optical fiber using a microscope objective and then guided to a superconducting single photon detector (SSPD). For the time resolved measurements, a histogram of photon arrival times was built by correlating the SSPD output with the PPG trigger with a correlation card.

We achieve ns and sub-ns switching time responses at 9.5 K and at RT, respectively, Fig. 2(a-left). The fast spontaneous decay rates at RT are in good agreement with the modelling results using rate equations, Fig. 2(a-right), confirming that the fast non-radiative recombination is dominant at RT enabling sub-ns modulation. Further speed increase, Fig. 2(b), is achieved by operating at low bias pumping to obtain a full turn-off cycle of the modulation, enabling a fast sweep-out of carriers from the InGaAs active region. The high-speed modulation results represent a step forward in providing ultrafast nanoscale light sources for optical interconnects in nanophotonic circuits.

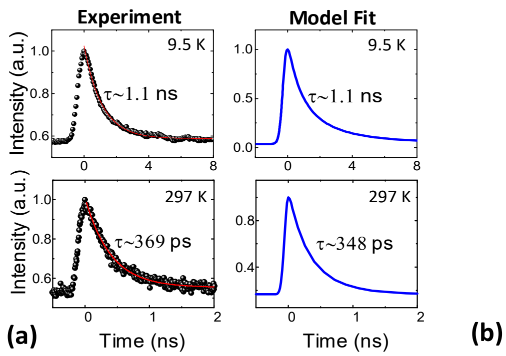

Fig. 2. (a) Experimental (left) and numerical simulated (right) direct modulation operation at 9.5 K and RT. (b) High-speed modulation at RT varying the bias current revealing sub-100 ps switch-off. In all plots, the modulation was a 80 MHz pulsed signal (100 ps width).

References

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